LA-UR-21-24048
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Title: Dust Formation and Growth in Core Collapse Supernovae Explosions

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Intended for: Institutional PhD. General Exam Presentation

Issued: 2021-04-27

Dust Formation and Growth in Core Collapse Supernovae Explosions

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April 29, 2021

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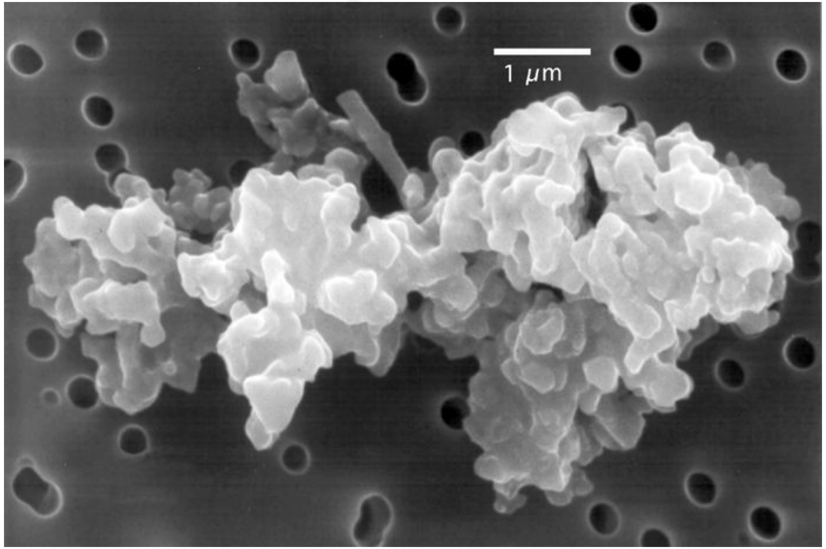


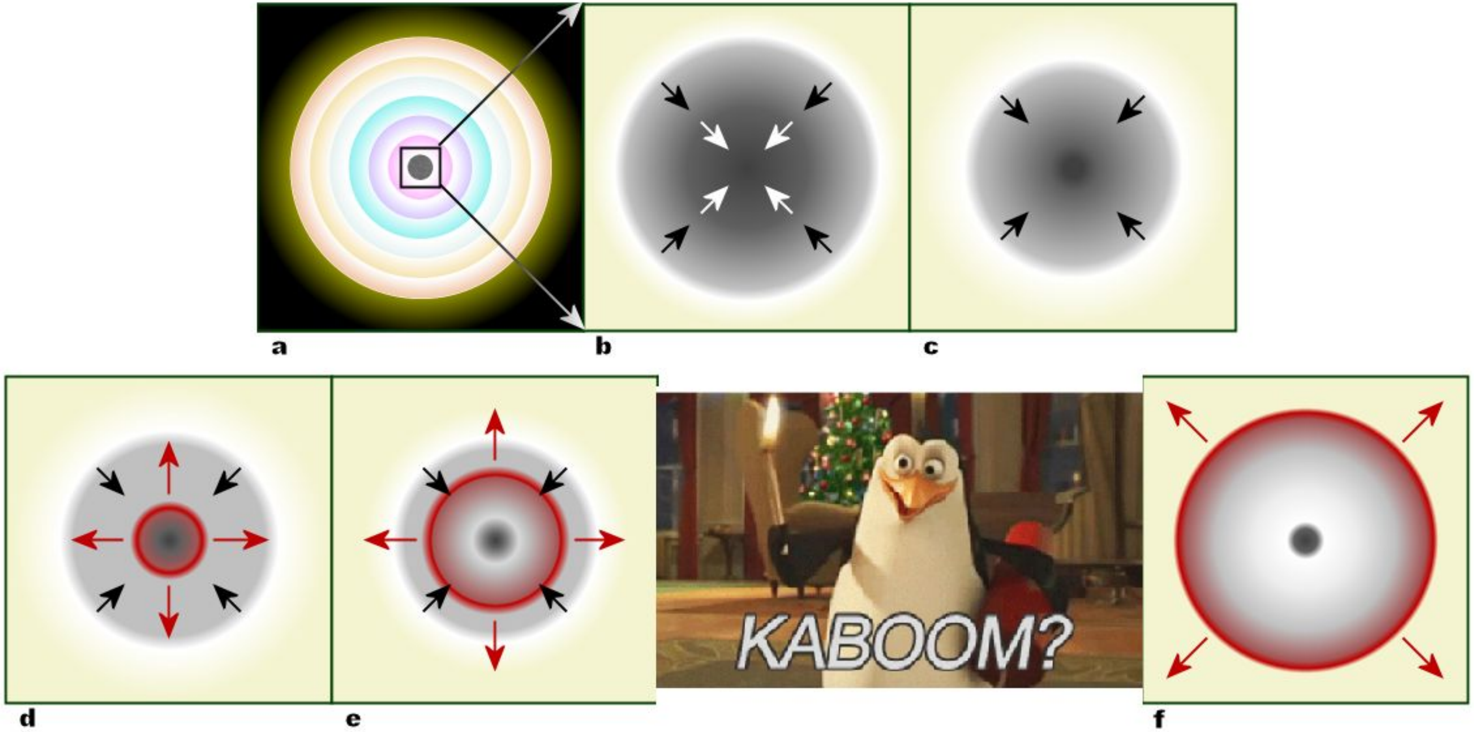
What is Dust?

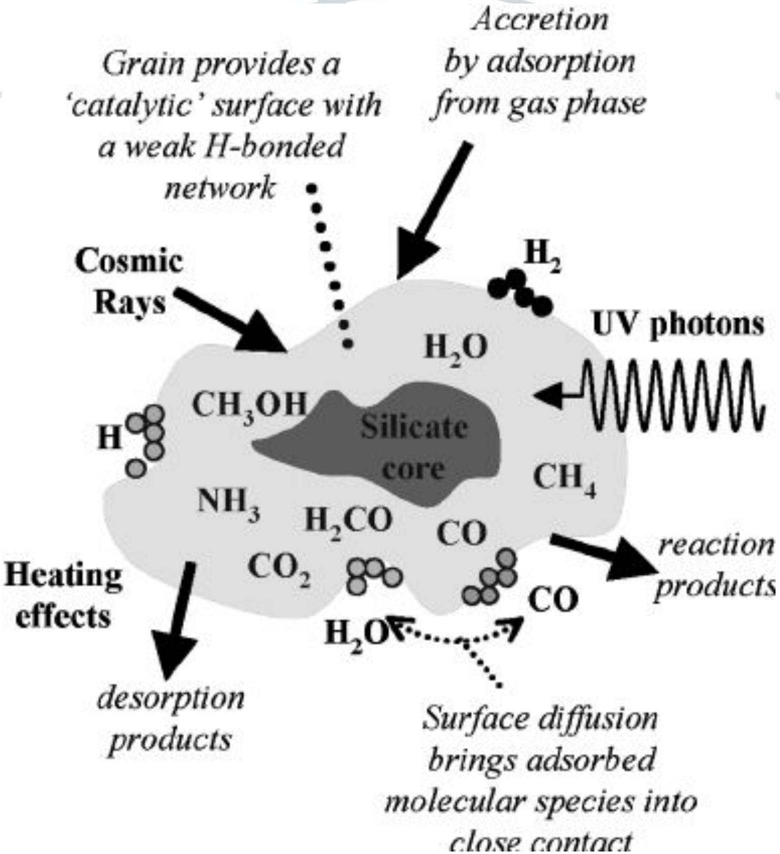
- a few molecules to ~100 μm
- AGB Atmospheres
  - cool, extended envelope
  - Stellar wind: dust -> ISM
- Supernova Outflows
  - ejecta expands and cools, dust grains nucleate
- Formation in Cold ISM
  - grains can form and grow on existing grains
- Not sure what fraction of dust from each one

Why Care about Dust?

- Ubiquitous
- Absorbs and re-emits light in longer wavelengths
- Seed for more complicated molecules
- Enriches ISM, proto-galaxies/stars
- Vital to early stellar and galactic formation and evolution
- Pre-Solar grains: isotopic signature of stars + fusion processes
- Molecular lines: composition of object and underlying physics
- Multi-Messenger signal

Core Collapse Supernovae (CCSNe)





Grain provides a 'catalytic' surface with a weak H-bonded network
Accretion by adsorption from gas phase
Cosmic Rays
H2
UV photons
H2O
CH3OH
Silicate core
H
NH3
H2CO
CO
CH4
reaction products
Heating effects
CO2
CO
H2O
desorption products
Surface diffusion brings adsorbed molecular species into close contact

This Project’s Goal

- How initial CCSNe parameters (explosion energy, type, progenitor mass, abundances, etc.) affect the amount, type, and size of dust grains produced
  - Gain insight into the Supernova engine

- What fraction of dust is produced in CCSNe?

Gas Chemistry (Sluder et al. 2018)

- Ion recombination occurs. Molecules form from gas-phase reactions as the material cools.
- Material condenses out of the gas phase onto the outside of the dust grain
- For reaction, the number density of the species change depending on the reaction's rate coefficient and the number density of the reactant.

$$\frac{dn}{dt} = \Sigma Production - Loss$$

$$C + C + M \rightarrow C_2 + M$$
$$C + N + M \rightarrow CN + M$$
$$C + O + M \rightarrow CO + M$$

Formation of Dust - Key Species

- Nucleation rate
  - governed by key species
    - the reaction rate is much larger than the decay rate
    - species with the least collisional frequency, controls nucleation and growth

Grains	Key Species	Chemical Reactions
$Fe_{(s)}$	$Fe_{(g)}$	$Fe_{(g)} \rightarrow Fe_{(s)}$
$FeS_{(s)}$	$Fe_{(g)}$, $S_{(g)}$	$Fe_{(g)} + S_{(g)} \rightarrow FeS_{(s)}$
$Si_{(s)}$	$Si_{(g)}$	$Si_{(g)} \rightarrow Si_{(s)}$
$Ti_{(s)}$	$Ti_{(g)}$	$Ti_{(g)} \rightarrow Ti_{(s)}$
$V_{(s)}$	$V_{(g)}$	$V_{(g)} \rightarrow V_{(s)}$
$Cr_{(s)}$	$Cr_{(g)}$	$Cr_{(g)} \rightarrow Cr_{(s)}$
$Co_{(s)}$	$Co_{(g)}$	$Co_{(g)} \rightarrow Co_{(s)}$
$Ni_{(s)}$	$Ni_{(g)}$	$Ni_{(g)} \rightarrow Ni_{(s)}$
$Cu_{(s)}$	$Cu_{(g)}$	$Cu_{(g)} \rightarrow Cu_{(s)}$
$C_{(s)}$	$C_{(g)}$	$C_{(g)} \rightarrow C_{(s)}$
$SiC_{(s)}$	$Si_{(g)}$, $C_{(g)}$	$Si_{(g)} + C_{(g)} \rightarrow SiC_{(s)}$
$TiC_{(s)}$	$Ti_{(g)}$, $C_{(g)}$	$Ti_{(g)} + C_{(g)} \rightarrow TiC_{(s)}$
$Al_2O_{3\,(s)}$	$Al_{(g)}$	$2Al_{(g)} + 3O_{(g)} \rightarrow Al_2O_{3\,(s)}$
$MgSiO_{3\,(s)}$	$Mg_{(g)}$, $SiO_{(g)}$	$Mg_{(g)} + SiO_{(g)} + 2O_{(g)} \rightarrow MgSiO_{3\,(s)}$
$Mg_2SiO_{4\,(s)}$	$Mg_{(g)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4\,(s)}$
	$SiO_{(g)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4\,(s)}$
$SiO_{2\,(s)}$	$SiO_{(g)}$	$SiO_{(g)} + O_{(g)} \rightarrow SiO_{2\,(s)}$
$MgO_{(s)}$	$Mg_{(g)}$	$Mg_{(g)} + O_{(g)} \rightarrow MgO_{(s)}$
$Fe_3O_{4\,(s)}$	$Fe_{(g)}$	$3Fe_{(g)} + 4O_{(g)} \rightarrow Fe_3O_{4\,(s)}$
$FeO_{(s)}$	$Fe_{(g)}$	$Fe_{(g)} + O_{(g)} \rightarrow FeO_{(s)}$

Nozawa et al. 2003

Dust Growth via grain nucleation

- Growth (key species)
  - material collides and sticks to the grain
  - once the key species is used up, reaction stops
  - abundance of key species is determined by a system of coupled nonlinear ODEs

$$\frac{dr_j}{dt} = \alpha_{sj}\Omega_j\left(\frac{kT}{2\pi m_{1j}}\right)^{1/2}$$

$$c_{1j}(t) = \frac{1}{3}a_{0j}\tau^{-1}_{\mathrm{coll},j}(t)$$

- Moment Equations

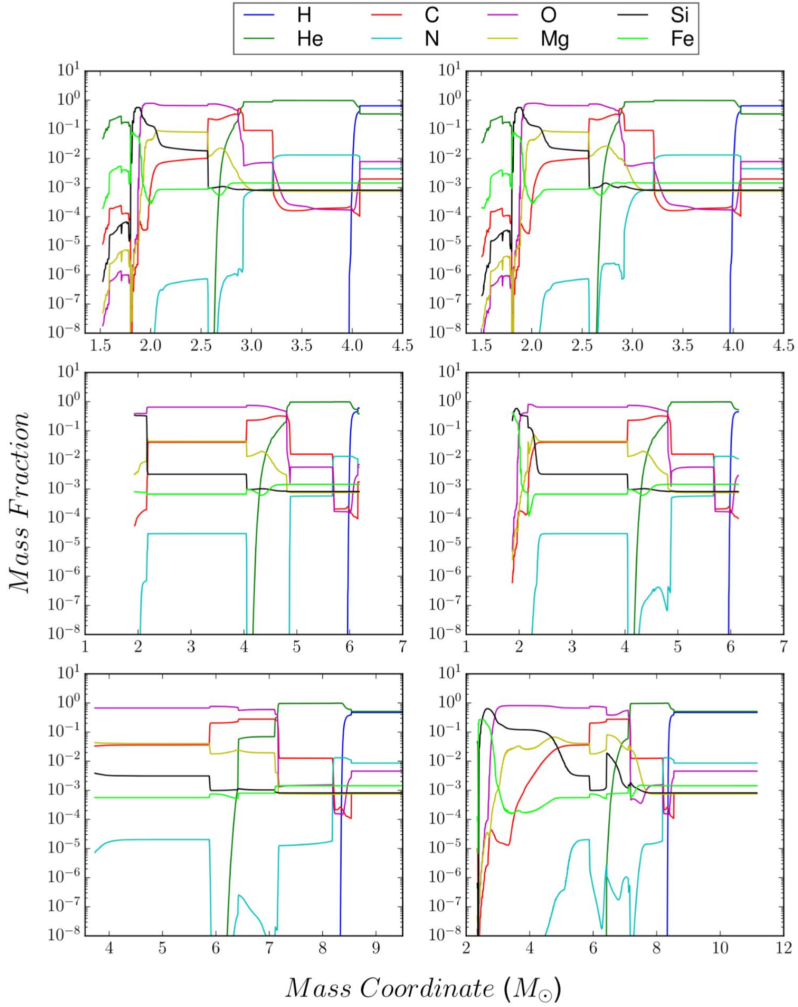
$$\frac{dK_j^{(0)}}{dt} = \frac{J_j(t)}{\tilde{c}_{1j}(t)}\frac{4\pi}{3\Omega_j}$$

$$\frac{dK_j^{(i)}}{dt} = \frac{J_j(t)}{\tilde{c}_{1j}(t)}\frac{4\pi}{3\Omega_j}r^i_{c,j} + iK_j^{(i-1)}\frac{dr_j}{dt}\ (\text{for } i = 1\text{–}3)$$

K0: grain number density, K1: average radius, K2: average surface area, K3: key species depletion

CCSNe Models

- Models (Fryer et al. 2018)
  - Progenitor mass: 15, 20, 25 $M_\odot$
  - Explosion energy: 0.5 - 125 foe
    - Sudden energy injection from convective engine
    - Prolonged energy injection from magnetor or fallback accretion
  - Unmixed ejecta: No Mixing!
  - 1-D: assumes spherical symmetry



Hydrocode

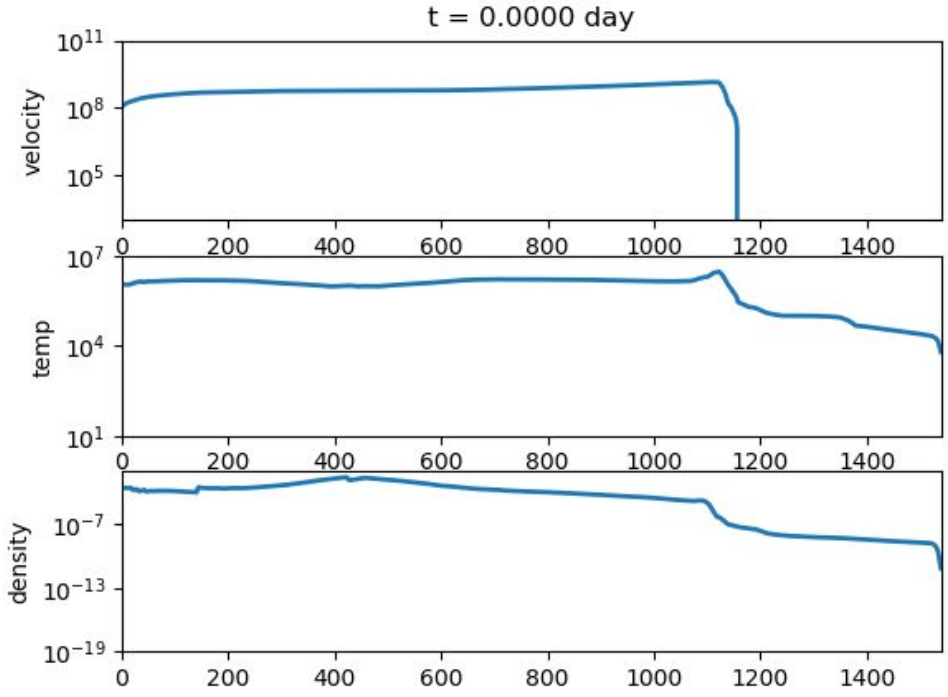
- 1-D Lagrangian: Mass-centered mesh
- Remove compact core
- Add thermal stellar wind profile onto the stellar surface
- Evolve ejecta out to 1157 days
  - Allows for cooling and expansion of ejecta to values agreable to dust formation

Code

- *nuDust*: **nu**cleating **dust** code in python
- Takes in composition and hydrodynamical profiles
- Pre-formation of CO and SiO gas phase molecules
- Solves system of coupled nonlinear ODEs for all grain species simultaneously
    - LSODA integrator
        - switches between the nonstiff Adams method and the stiff BDF method
- *Numba* for just-in-time (*JIT*) compilation to increase efficiency and optimization
- Parallelization: *multiprocessing* library

Hydro Results

15 SM, 1.69 Foe

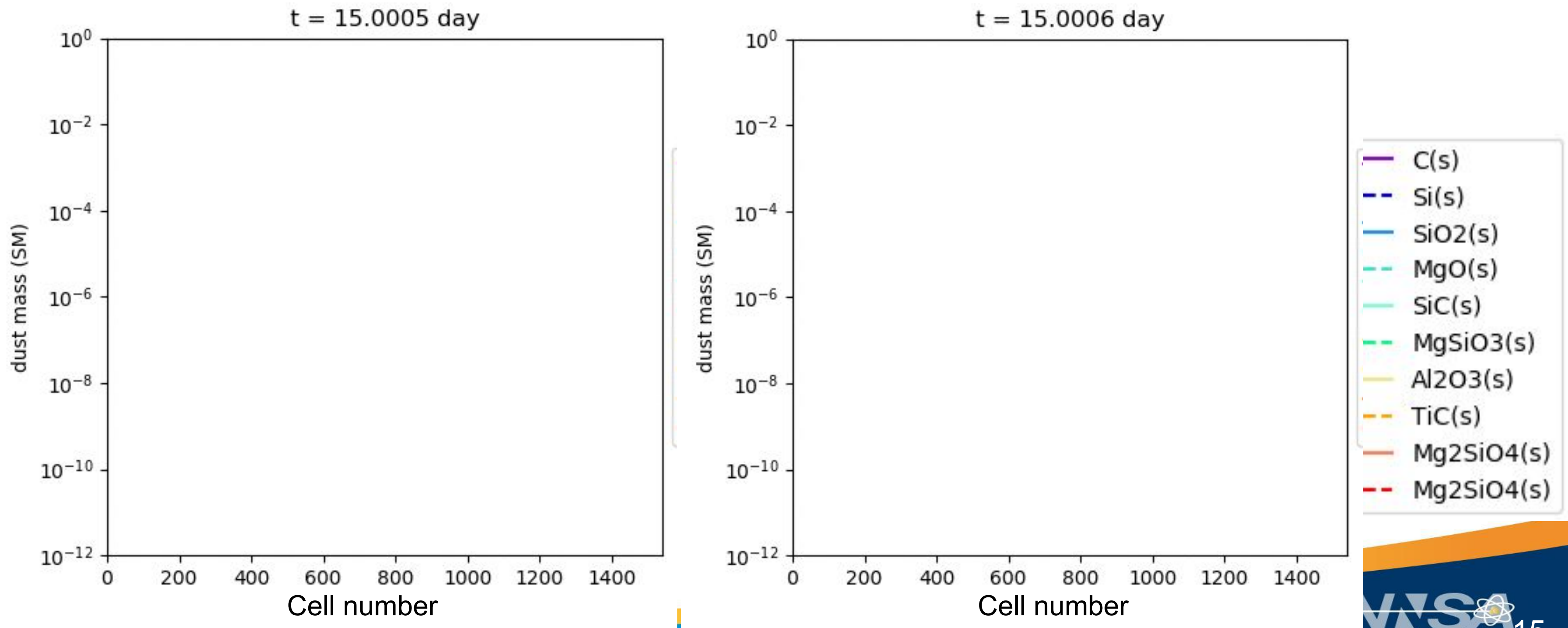


Cell number

Dust Formation

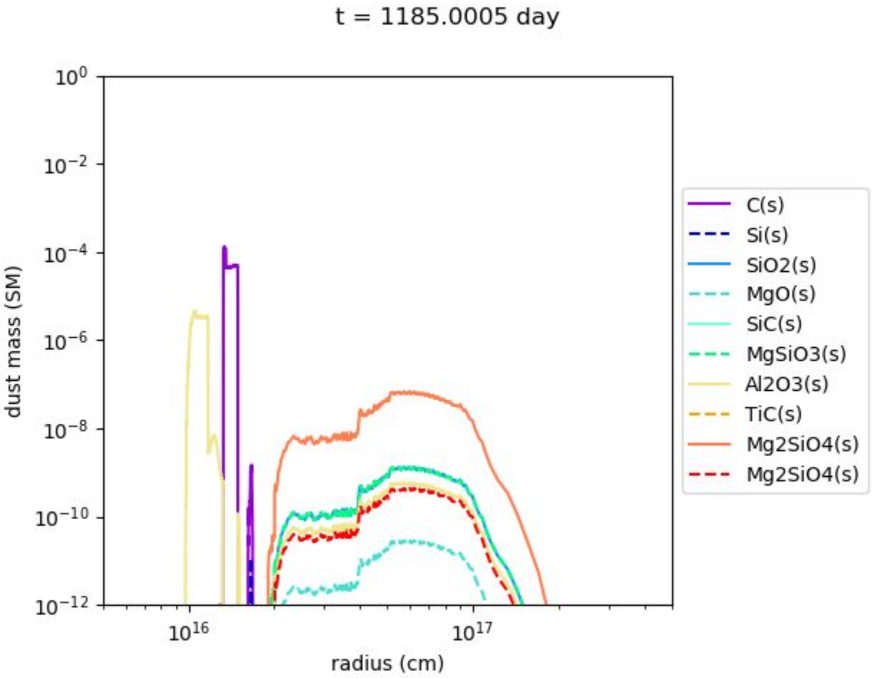
15 SM, 2.47 Foe

20 SM, 2.85 Foe

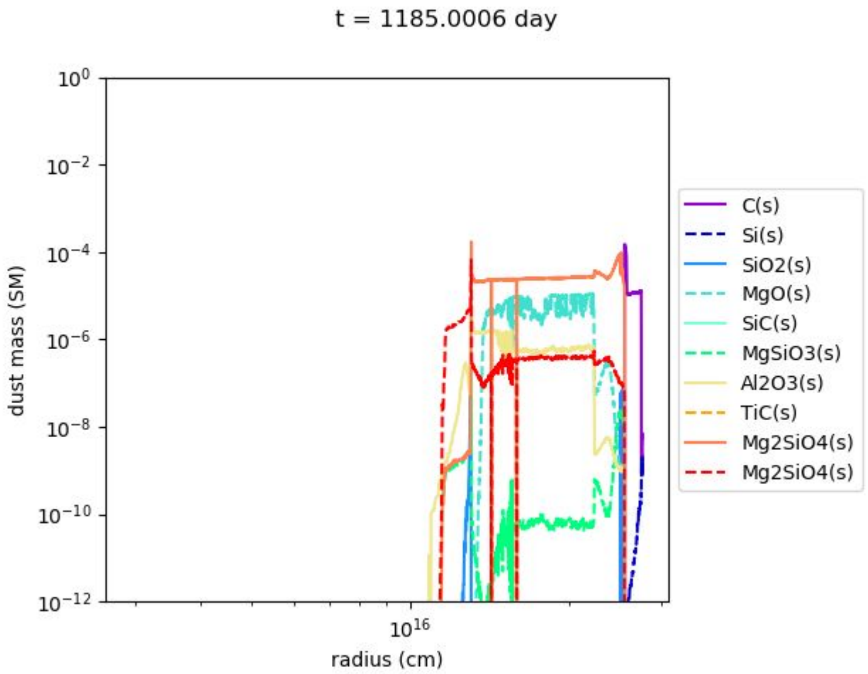


Dust Formation

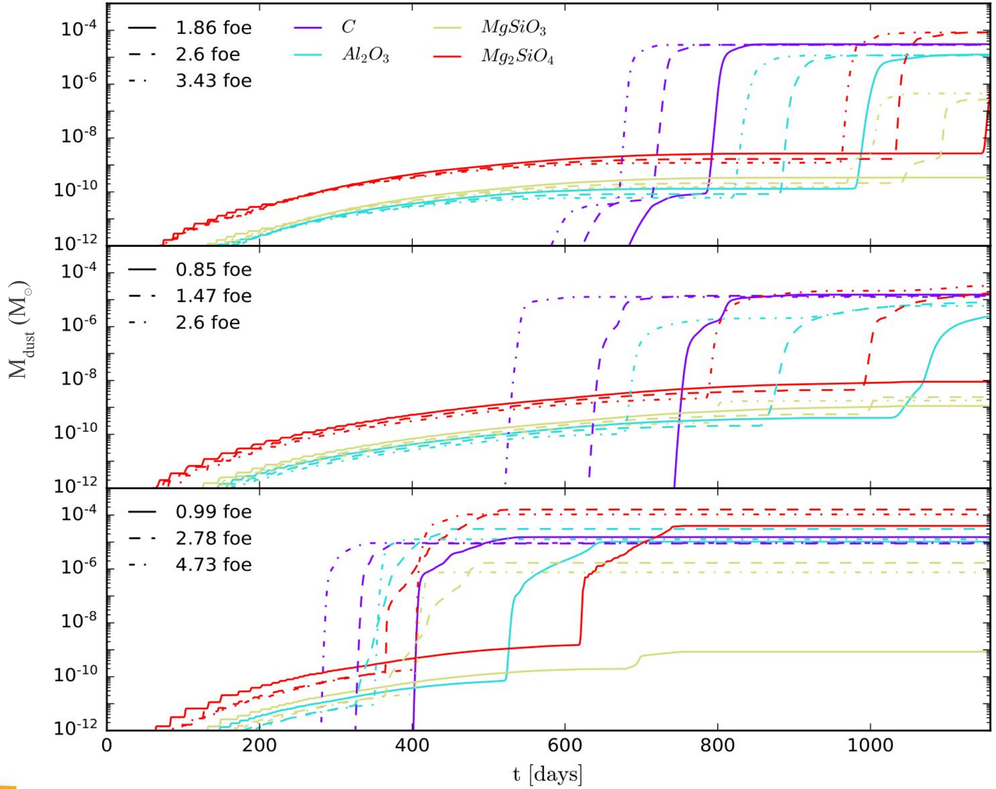
15 SM, 2.47 Foe



20 SM, 2.85 Foe



Formation Time

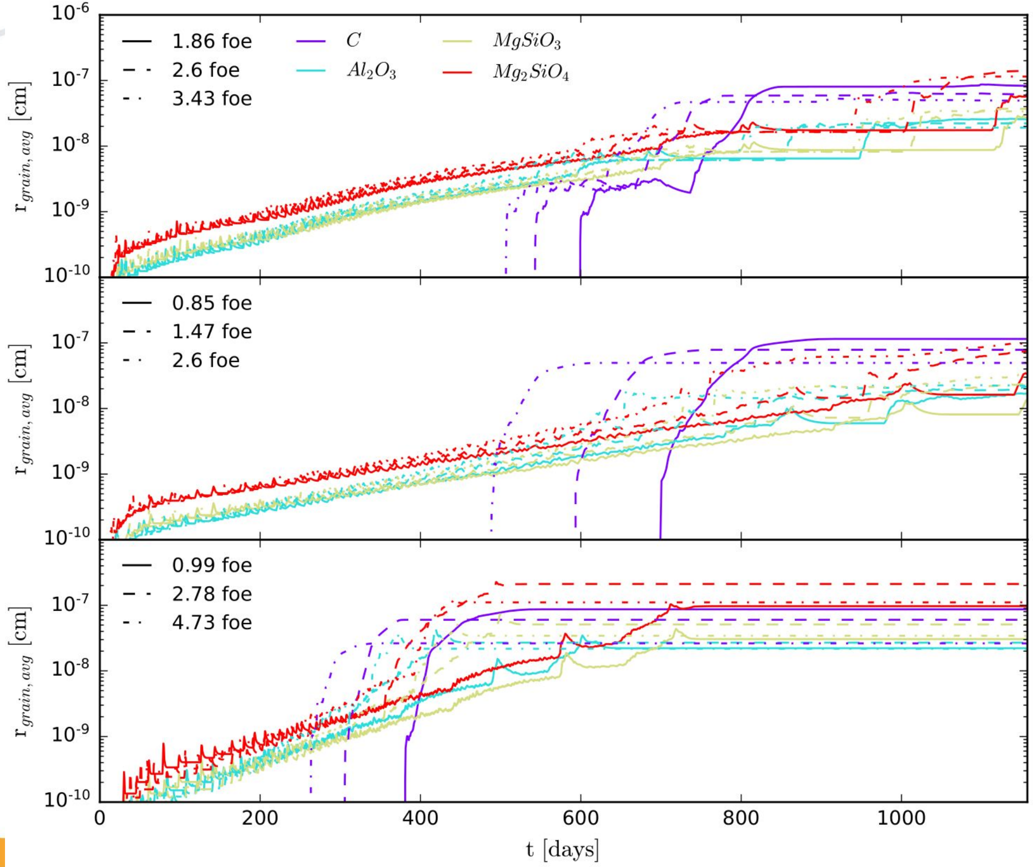


15 $M_\odot$

20 $M_\odot$

25 $M_\odot$

Average Grain Size

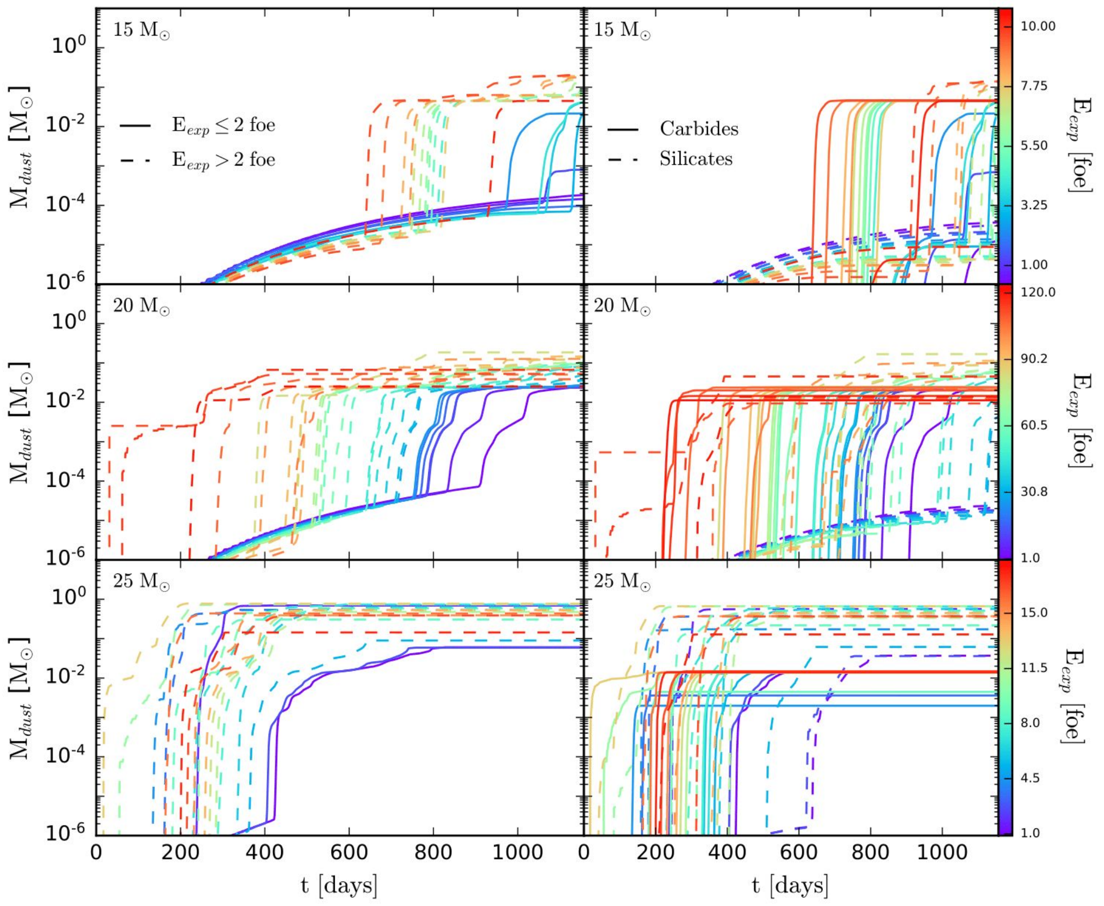


15 $M_\odot$

20 $M_\odot$

25 $M_\odot$

Dust Mass



15 M☉

20 M☉

25 M☉

Future Work

- Include more physics
  - Shock destruction, gas chemistry, radioactive decay, mixing,etc.
- Hydrocode in 2-D and 3-D
- Code performance testing + optimization
- Produce Spectra + Light Curves
  - Look for impacts of grains on spectral lines
- Compare dust and spectra with Observations
  - SN IIb?
  - Identify obs. object’s characteristics from dust

Conclusions

- ***How do CCSNe conditions affect dust production?***
  - Dust formation occurs earlier in high energy explosions
    - Ejecta expands/cools faster
  - Larger grains form in low energy explosions
    - expands/cools slower--longer growth time period
  - Bulk formation of carbon occurs earlier than silicates
  - Higher explosion energies produce more dust
- ***How much dust is produced in CCSNe?***
  - 10^{-1}-10^{-5} $M_\odot$ dust: upper bound
    - 10^{-1}-10^{-2} $M_\odot$ most common

Acknowledgements

This work was funded by the Los Alamos National Laboratory and the New Mexico Consortium

Collaboration with Ezra Brooker (FSU), Christopher Mauney (LANL), and Christopher Fryer (LANL)

Thank you for Listening!!

Backups

Gas Grain Interactions

- Adsorption
  - gas-phase species sticks to the grain surface

$$k_{\rm ads}(i) = \sigma_{\rm d}\langle v(i)\rangle n(i) n_{\rm d},$$

- Desorption
  - surface species break away into the gas-phase
  - thermal (Ed = desorption E, ν= vibrational frequency)

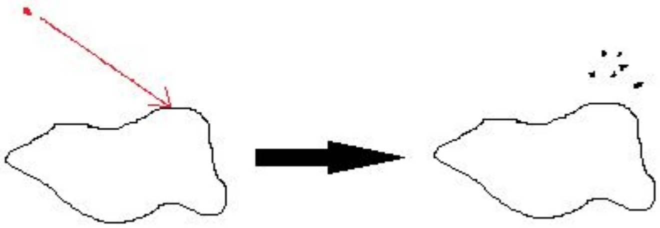
$$k_{\rm des}(i) = \nu_0(i)\exp\left(-\frac{E_{\rm D}(i)}{T_{\rm g}}\right),$$

  - non-thermal
    - cosmic ray ionization rate
    - fraction of time T = 70 K

Sputtering

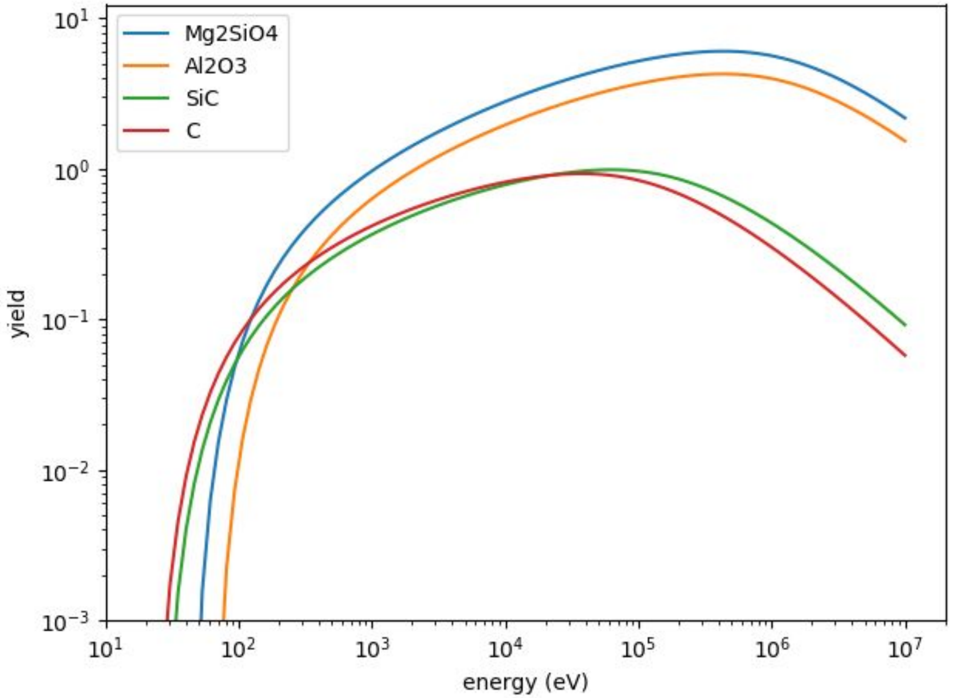
- Chemical: incoming gas or reactive ion interacts with the grain's surface forming an unstable compound
  - the instabilities cause material to sputter off the grain's surface
  - occurs at low energies

- Physical: kinetic energy from the colliding ion/particle is transferred to the grain
  - with enough energy to overcome surface binding forces, material sputters off the grain
  - occurs at high energies



Sputtering Yield

- The amount of sputtered atoms per ion.
- Depends on the nuclear stopping cross section, surface binding energy, the threshold energy (min KE), and the energy of the incoming particle.



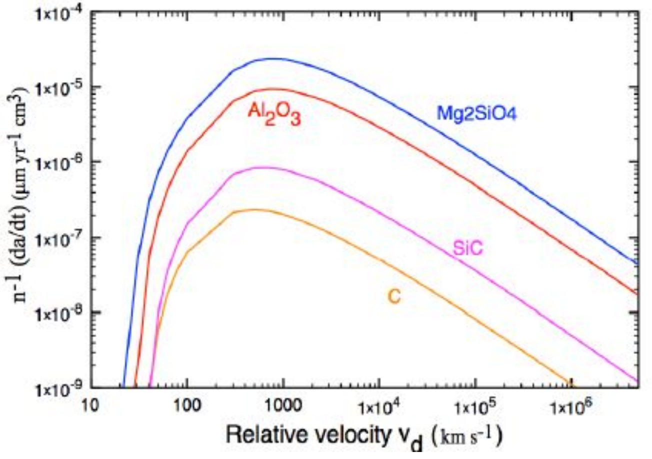
Grain Erosion Rate

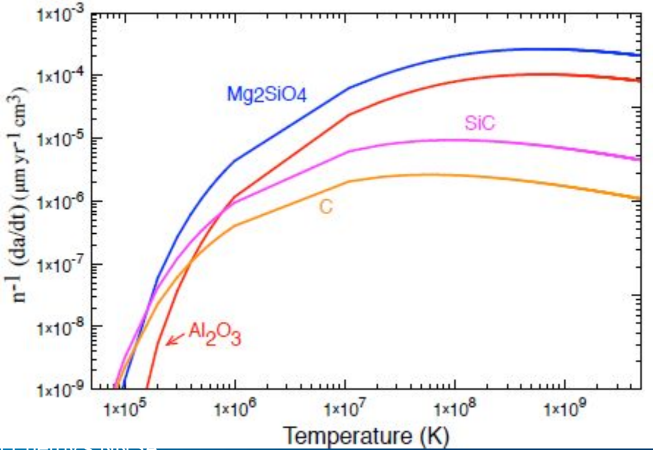
- Non-thermal sputtering: non-thermal sputtering erodes a hypersonic grain

$$\frac{1}{n_H}\frac{da}{dt} \approx -v_d \sum A_i Y_i(E = 1/2 m_i v_d^2)$$

- Thermal sputtering: the grain moves with the shock and collide with the ionized gas

$$\frac{1}{n_H}\frac{da}{dt} \approx -\sum A_i \left(\frac{8kT}{\pi m_i}\right) \int \epsilon_i e^{-\epsilon_i} Y_i(\epsilon_i) d\epsilon_i$$

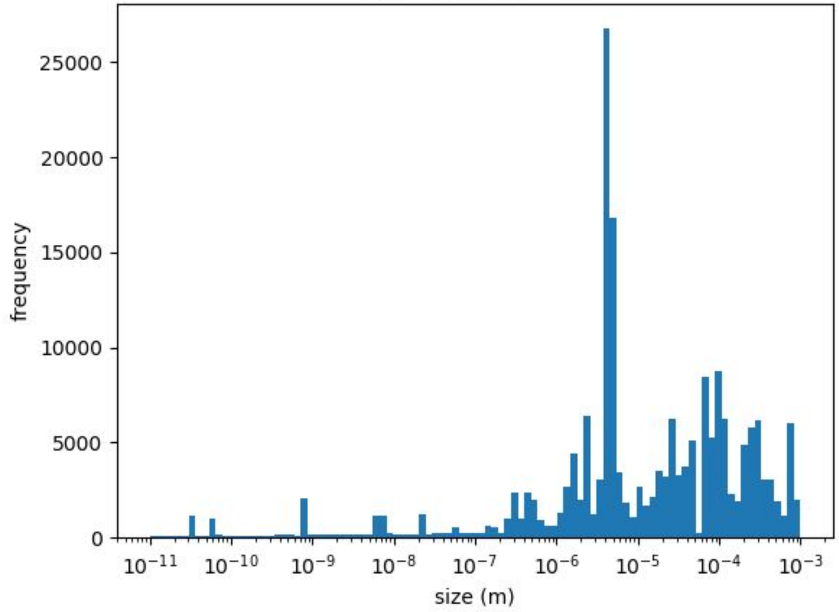




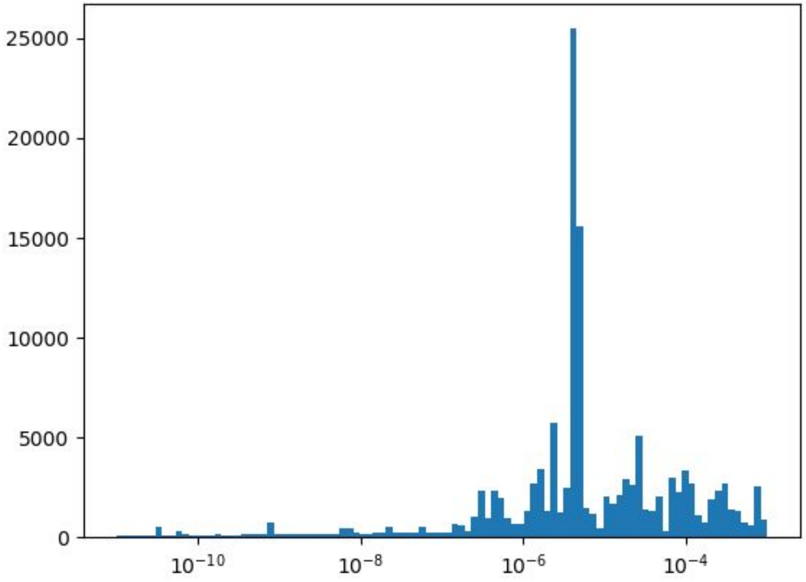
Dust Destruction

15 SM, 2.63 Foe, C grains

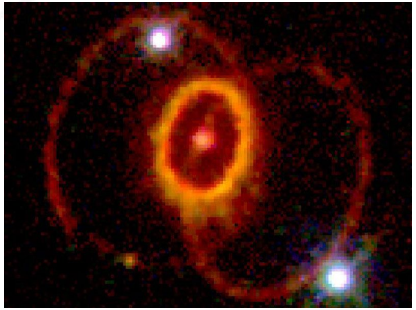
No shock

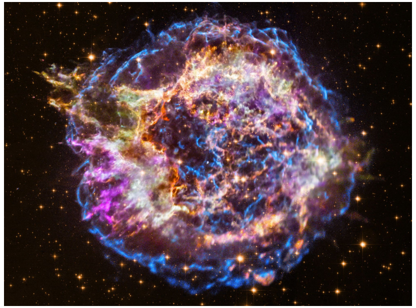


Shock Destruction



Scaling up and model complexity





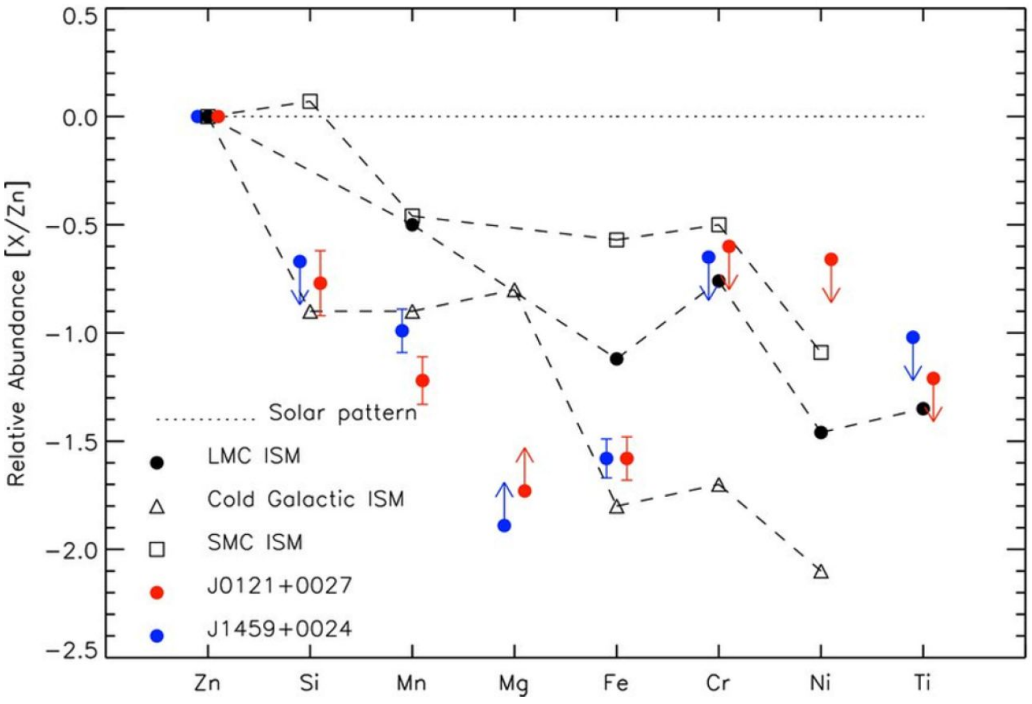
CCSNe are 3-D, dust production is as well

Extend physics model (gas chemistry, shock destruction, radioactive decay, etc)

Scaling up and increasing complexity requires more efficient code

Gas-Phase Depletion

- Heavier elements condense out at higher temperatures
- They aren't as susceptible to sputtering
- Environment affects exact trend



Peng Jiang, Jian Ge, J. Prochaska, & Junfeng Wang 2010

Complex Molecules

- In the ISM
  - low number density, high KE, and high repulsion between dipoles
- You need a seed nucleus: dust grains
- Single atoms bond to the grain, the grain absorbs excess energy, through quantum tunneling the atoms migrate on the surface and bond.
  - Repulsion energy for H, 19.4 eV